$D_{sJ}^+(2632)$: An Excellent Candidate of Tetraquarks

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We analyze various possible interpretations of the narrow state $D_{sJ}(2632)$ which lies 100 MeV above threshold. This interesting state decays mainly into $D_s\eta$ instead of D^0K^+. If this relative branching ratio is further confirmed by other experimental groups, we point out that the identification of $D_{sJ}(2632)$ either as a $c\bar{s}$ state or more generally as a $\bar{\mathbf{3}}$ state in the $SU(3)_F$ representation is probably problematic. Instead, such an anomalous decay pattern strongly indicates $D_{sJ}(2632)$ is a four quark state in the $SU(3)_F$ $\mathbf{15}$ representation with the quark content $\frac{1}{2\sqrt{2}}(ds\bar{d}+sd\bar{d}+su\bar{u}+us\bar{u}-2ss\bar{s})\bar{c}$. We discuss its partners in the same multiplet, and the similar four-quark states composed of a bottom quark $B_{sJ}^0(5832)$. Experimental searches of other members especially those exotic ones are strongly called for.

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I. INTRODUCTION

The experimental discovery of the low-lying narrow charm mesons $D_{sJ}(2317)$ and $D_{sJ}(2457)$ [1, 2, 3, 4] has attracted much attention. Since their masses in the constituent quark model are roughly 160 MeV higher than the experimental values, some people postulated these states could be a four quark state [5, 6]. However, there is no compelling evidence that $D_{sj}(2317)$ and $D_{sJ}(2457)$ are non-conventional meson states. It is still possible to interprete them as $c\bar{s}$ states [7, 8]. Instead, the large electromagnetic branching ratio of $D_{sJ}(2457)$ favors such a picture [3, 4]. Interested readers may consult Ref. [9] for a nice review of this topic.

Very recently SELEX Collaboration observed another exotic charm-strange meson $D_{sJ}(2632)$ with a significance of 7.2σ in the $D_s\eta$ channel and 5.3σ in the D^0K^+ channel [10], which has created some excitement [13, 14, 15, 16, 17]. The decay width of this narrow resonance is less than 17 MeV at 90% confidence level.

At present there are three puzzles concerning this state. First, this state lies 274 MeV above D^0K^+ threshold and 116 MeV above $D_s\eta$ threshold. One would naively expect its strong decay width to be around $(100 \sim 200)$ MeV. Both particles in the final states are pseudoscalar mesons, thus $D_{sJ}^+(2632)$ has $J = L, P = (-)^L$ with L being the decay angular momentum. Because the final states D_s^+ and η are both isoscalar, $D_{sJ}^+(2632)$ is probably an isoscalar.

Secondly, the ground state charm-strange mesons with $L = 0$ are $D_s(1968)$ and $D_s^*(2112)$. According to the heavy quark effective field theory, there exist two heavy doublets with positive parity and $L = 1$. We denote them as $l^P = \frac{1}{2}^+$ and $l^P = \frac{3}{2}^+$ where l is the angular momentum of the light quark. The $l^P = \frac{1}{2}^+$ doublet are $D_{sJ}(2317)$ and $D_{sJ}(2457)$. The $l^P = \frac{3}{2}^+$ doublet are $D_{sJ}(2536)$ and $D_{sJ}(2573)$ [11]. One may be tempted to interpret $D_{sJ}(2632)$ either as a member of the $l^P = \frac{5}{2}^-$ doublet with $J = 3, L = 2$ or as a member of the $l^P = \frac{3}{2}^-$ doublet with $J = 1, L = 2$. Especially the identification of $D_{sJ}(2632)$ as a $J = 3, L = 2$ state may seem attractive at first sight since the presence of the high angular momentum may lead to a small decay width. But apparently $D_{sJ}(2632)$ is too low for $L = 2$! Another possibility is that $D_{sJ}(2632)$ is the first radial excitation of the ground state charm-strange meson [16].

The most demanding issue is the unusual decay pattern. This state decays mainly into the $D_s\eta$ mode. Recall that SU(3) flavor symmetry breaking is at most around 20% and the physical eta meson is mainly an octet. One may perform a more refined analysis taking into account the mixing between η_8 and η_1 or the SU(3) symmetry breaking effects. But the following result will not change dramatically. We may write an effective Lagrangian for $D_{sJ}(2632)$ decay processes if it is a $c\bar{s}$ state. The decay width reads

$$\Gamma = \lambda^2 g^2 \frac{k^{2L+1}}{m^{2L}}, \tag{1}$$

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where λ is the C.G. coefficient, g is the universal and dimension-less effective coupling constant, L is the angular momentum for decay. m is the parent mass and k is the decay momentum in the center of mass frame

$$k = \frac{1}{2m}\{[m^2 - (m_1 + m_2)^2][m^2 - (m_1 - m_2)^2]\}^{\frac{1}{2}}, \tag{2}$$

where m_1 and m_2 are the masses of final mesons. The ratio of decay widths of these two channels is

$$\frac{\Gamma(D^0K^+)}{\Gamma(D_s\eta)} = (\frac{\lambda_{D^0K^+}}{\lambda_{D_s\eta}})^2(\frac{k_{D^0K^+}}{k_{D_s\eta}})^{2L+1}. \tag{3}$$

Using $\frac{\lambda_{D^0K^+}}{\lambda_{D_s\eta}} = \sqrt{\frac{3}{2}}$, $k_{D^0K^+} = 499$ MeV, $k_{D_s\eta} = 325$ MeV, we get

$$\frac{\Gamma(D^0K^+)}{\Gamma(D_s\eta)} = 2.3 * (1.54)^{2L} \geq 2.3. \tag{4}$$

which is nearly 15 times larger than the experimental value [10]

$$\frac{\Gamma(D^0K^+)}{\Gamma(D_s\eta)} = 0.16 \pm 0.06\ . \tag{5}$$

If this relative branching ratio is confirmed by other experimental groups, we conclude that the identification of $D_{sJ}(2632)$ either as a $c\bar{s}$ state or more generally as a $\bar{\mathbf{3}}$ state in the $SU(3)_F$ representation is very problematic. We must seek other interpretations.

$D_{sJ}(2632)$ decays mainly into $D_s\eta$. η is a mixture of η_8 and η_1. η_1 is a SU(3) singlet which mixes strongly with $G\tilde{G}$. One may think $D_{sJ}(2632)$ is a good candidate of heavy hybrid meson with the content $cG\bar{s}$ [12]. If it is the lowest hybrid state, one should expect that it is composed of $c, \bar{s}$ and a gluon of magnetic field type (all in S state) so that it has spin-parity 1^-. For decay of this state to D_s and η, the quark should emit a gluon of electric field type in S state so that the gluon component has total spin-parity 0^-. However, in this transition the quark component must jump to the excited state due to selection rule contrary to the experiment observation. If the initial state is not the lowest hybrid state, its mass should be heavier than the observed mass. The hybrid state with two explicit gluons $G\tilde{G}$ also seems to be too heavy. However, the gluon is a flavor singlet. So the hybrid assumption can not explain the unusual decay pattern.

Since $D_{sJ}(2632)$ is above threshold, it can't be a hadron molecule state. Molecules are bound states of color singlet hadrons. They should lie near or below threshold. However, it could be a bound state of two color non-singlet clusters like a diquark and anti-diquark. That's what we will advocate below: $D_{sJ}(2632)$ is a four quark state which provides a simple and natural explanation of the unusual decay pattern.

II. TETRAQUARK MULTIPLETS

In this section, we consider a tetraquark state $qq\bar{q}\bar{c}$ with $q = u, d, s$. We present the wave functions and the decay modes of the tetraquark states with one anti-charm quark.

Under the transformation of $SU(3)_F$, the charm quark is singlet. There are four multiplets according to

$$3 \otimes 3 \otimes \bar{3} \otimes 1 = 3 \oplus 3 \oplus \bar{6} \oplus 15\ . \tag{6}$$

In these tetraquark multiplets, all states have charm number $C = -1$. We denote the states with strangeness $S = 1$ as $D_{\bar{s}}$, with $S = 0$ as D, with $S = -1$ as D_s and with $S = -2$ as D_{ss}. The weight diagrams are shown in Fig. 1.

We present all the tetraquark flavor wave functions in Table I-III. These expressions are obtained by operating U_- and I_- operators on the highest weight state.

As we have pointed out, $D_{sJ}(2632)$ can not be a member of $\bar{3}$ representation. From now on, we focus on the $\bar{6}, 15$ representations. We can get the decay modes of these tetraquark states by expanding the following effective Lagrangian

$$L_{eff} = g_6 T^{\dagger ij} M_i^a T^b \epsilon_{abj} + g_{15} T^{\dagger i}_{jm} M_i^j T^m\ , \tag{7}$$

where the triplet T^i reads

$$(T^i) = \begin{pmatrix} \bar{c}u \\ \bar{c}d \\ \bar{c}s \end{pmatrix} = \begin{pmatrix} \bar{D}^0 \\ D^- \\ D_s^- \end{pmatrix}. \tag{8}$$

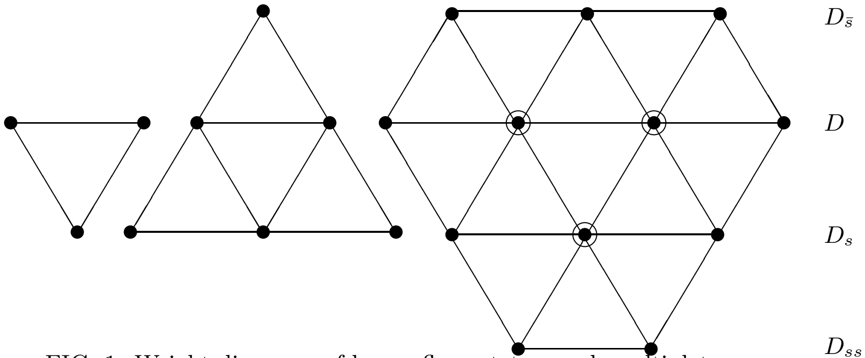

FIG. 1: Weight diagrams of heavy flavor tetraquark multiplets.

	States	Flavor Wave Functions	States	Flavor Wave Functions
$I=\frac{1}{2}, S=0$	$\bar{D}_3^0$	$\frac{1}{2}(su\bar{s}-us\bar{s}-ud\bar{d}+du\bar{d})\bar{c}$	$\bar{D}_3^{0\prime}$	$\frac{1}{2\sqrt{2}}(su\bar{s}+us\bar{s}+ud\bar{d}+du\bar{d}+2uu\bar{u})\bar{c}$
	D_3^-	$\frac{1}{2}(ud\bar{u}-du\bar{u}-ds\bar{s}+sd\bar{s})\bar{c}$	$D_3^{-\prime}$	$\frac{1}{2\sqrt{2}}(ud\bar{u}+du\bar{u}+ds\bar{s}+sd\bar{s}+2dd\bar{d})\bar{c}$
$I=0, S=-1$	$D_{s,3}^-$	$\frac{1}{2}(ds\bar{d}-sd\bar{d}-su\bar{u}+us\bar{u})\bar{c}$	$D_{s,3}^{-\prime}$	$\frac{1}{2\sqrt{2}}(ds\bar{d}+sd\bar{d}+su\bar{u}+us\bar{u}+2ss\bar{s})\bar{c}$

TABLE I: The flavor wave functions of the heavy tetraquarks in the two triplets.

The tensor representation for anti-sextet is

$$(T_{ij}) \;=\; \begin{pmatrix} D^{--}_{s,\bar{6}} & -\frac{1}{\sqrt{2}}D^-_{s,\bar{6}} & \frac{1}{\sqrt{2}}D^-_{\bar{6}} \\ -\frac{1}{\sqrt{2}}D^-_{s,\bar{6}} & D^0_{s,\bar{6}} & -\frac{1}{\sqrt{2}}D^0_{\bar{6}} \\ \frac{1}{\sqrt{2}}D^-_{\bar{6}} & -\frac{1}{\sqrt{2}}D^0_{\bar{6}} & D^0_{\bar{s},\bar{6}} \end{pmatrix}. \tag{9}$$

The members of 15 representation are

- $Y=\frac{4}{3}, I=1,$

$$T_3^{11}=D^+_{\bar{s},15} \qquad T_3^{12}=\frac{1}{\sqrt{2}}D^0_{\bar{s},15} \qquad T_3^{22}=D^-_{\bar{s},15} \tag{10}$$

- $Y=\frac{1}{3}, I=3/2, 1/2$

$$T_2^{11}=-D^+_{15} \qquad T_1^{11}=\frac{1}{\sqrt{3}}D^0_{15}-\frac{1}{\sqrt{6}}D^{0\prime}_{15} \qquad T_2^{12}=-\frac{1}{\sqrt{3}}D^0_{15}-\frac{1}{2\sqrt{6}}D^{0\prime}_{15} \qquad T_3^{13}=\frac{\sqrt{6}}{4}D^{0\prime}_{15} \tag{11}$$

$$T_1^{12}=\frac{1}{\sqrt{3}}D^-_{15}-\frac{1}{2\sqrt{6}}D^{-\prime}_{15} \qquad T_2^{22}=-\frac{1}{\sqrt{3}}D^-_{15}-\frac{1}{\sqrt{6}}D^{-\prime}_{15} \qquad T_3^{23}=\frac{\sqrt{6}}{4}D^{-\prime}_{15} \qquad T_1^{22}=D^{--}_{15} \tag{12}$$

- $Y=-\frac{2}{3}, I=1,0$

$$\begin{aligned} &T_2^{13}=-\frac{1}{\sqrt{2}}D^0_{s,15} \qquad T_1^{13}=\frac{1}{2}D^-_{s,15}-\frac{\sqrt{2}}{4}D^{-\prime}_{s,15} \qquad T_2^{23}=-\frac{1}{2}D^-_{s,15}-\frac{\sqrt{2}}{4}D^{-\prime}_{s,15} \\ &T_3^{33}=\frac{1}{\sqrt{2}}D^{-\prime}_{s,15} \qquad T_1^{23}=\frac{1}{\sqrt{2}}D^{--}_{s,15} \end{aligned} \tag{13}$$

- $Y=-\frac{5}{3}, I=1/2$

$$T_2^{33}=-D^-_{ss} \qquad T_1^{33}=D^{--}_{ss}. \tag{14}$$

These expressions can also be obtained by using the isospin and U spin lowering operators.

We present the C.G. coefficient of each interaction term in Table IV and V. With these C.G. coefficients, it is easy to derive the relative branching ratio.

It is important to note that there is no isoscalar state with valence quark content $\bar{c}s$ in the anti-sextet. However, in the 15 tetraquark multiplet, there are an isoscalar $D^{-\prime}_{s,15}$. From Table V, we find the ratio of C.G. coefficients for $\bar{D}^0K^-$ channel and $D_s^-\eta_8$ channel is $\frac{1}{\sqrt{6}}$. Now the relative branching ratio reads

$$\frac{\Gamma(D^{-\prime}_{s,15}\to\bar{D}^0K^-)}{\Gamma(D^{-\prime}_{s,15}\to D_s^-\eta)} = 0.25*(1.54)^{2L} \tag{15}$$

	States	Flavor Wave Functions
$I=0, S=1$	$D^0_{\bar{s},\bar{6}}$	$\frac{1}{\sqrt{2}}(ud\bar{s}-du\bar{s})\bar{c}$
$I=\frac{1}{2}, S=0$	$D^0_{\bar{6}}$	$\frac{1}{2}(us\bar{s}-su\bar{s}-ud\bar{d}+du\bar{d})\bar{c}$
	$D^-_{\bar{6}}$	$\frac{1}{2}(ds\bar{s}-sd\bar{s}+ud\bar{u}-du\bar{u})\bar{c}$
$I=1, S=-1$	$D^0_{s,\bar{6}}$	$\frac{1}{\sqrt{2}}(su\bar{d}-us\bar{d})\bar{c}$
	$D^-_{s,\bar{6}}$	$\frac{1}{2}(sd\bar{d}-ds\bar{d}-su\bar{u}+us\bar{u})\bar{c}$
	$D^{--}_{s,\bar{6}}$	$\frac{1}{\sqrt{2}}(ds\bar{u}-sd\bar{u})\bar{c}$

TABLE II: The flavor wave functions of the heavy tetraquarks in the anti-sextet T_{ij}.

	States	Flavor Wave Functions
$I=1, S=1$	$D^+_{\bar{s},15}$	$us\bar{s}\bar{c}$
	$D^0_{\bar{s},15}$	$\frac{1}{\sqrt{2}}(ud\bar{s}+du\bar{s})\bar{c}$
	$D^-_{\bar{s},15}$	$dd\bar{s}\bar{c}$
$I=\frac{3}{2}, S=0$	D^+_{15}	$-uu\bar{d}\bar{c}$
	D^0_{15}	$-\frac{1}{\sqrt{3}}(ud\bar{d}+du\bar{d}-uu\bar{u})\bar{c}$
	D^-_{15}	$\frac{1}{\sqrt{3}}(ud\bar{u}+du\bar{u}-dd\bar{d})\bar{c}$
	D^{--}_{15}	$dd\bar{u}\bar{c}$
$I=\frac{1}{2}, S=0$	$D^{0\prime}_{15}$	$\frac{1}{2\sqrt{6}}[3us\bar{s}+3su\bar{s}-ud\bar{d}-du\bar{d}-2uu\bar{u}]\bar{c}$
	$D^{-\prime}_{15}$	$\frac{1}{2\sqrt{6}}[3ds\bar{s}+3sd\bar{s}-ud\bar{u}-du\bar{u}-2dd\bar{d}]\bar{c}$
$I=1, S=-1$	$D^0_{s,15}$	$-\frac{1}{\sqrt{2}}(su\bar{d}+us\bar{d})\bar{c}$
	$D^-_{s,15}$	$-\frac{1}{2}(ds\bar{d}+sd\bar{d}-su\bar{u}-us\bar{u})\bar{c}$
	$D^{--}_{s,15}$	$\frac{1}{\sqrt{2}}(ds\bar{u}+sd\bar{u})\bar{c}$
$I=0, S=-1$	$D^{-\prime}_{s,15}$	$-\frac{1}{2\sqrt{2}}(ds\bar{d}+sd\bar{d}+su\bar{u}+us\bar{u}-2ss\bar{s})\bar{c}$
$I=\frac{1}{2}, S=0$	D^-_{ss}	$-ss\bar{d}\bar{c}$
	D^{--}_{ss}	$ss\bar{u}\bar{c}$

TABLE III: The flavor wave functions of the heavy tetraquarks in 15-plet T^{ij}_k.

if we roughly assume $\eta \approx \eta_8$. This ratio is around 0.25 if $D^{-\prime}_{s,15}$ decays via S wave, which is consistent with the experimental result 0.16 ± 0.06. With P wave decay the relative ratio is about 0.59.

The above derivation of the ratio of the SU(3) Clebsch-Gordan coefficients is rather tedious. A straightforward way is to find these coefficients from available tables in literature. An exhaustive compilation of them is presented in Ref. [18]. When a particle A in the SU(3) representation R with hypercharge Y, isospin I, I_3 couples to particle B r, y, i, i_3 and particle C r', y', i', i'_3, the SU(3) Clebsch-Gordan coefficient can be decomposed into the product of an iso-scalar part and SU(2) Clebsch-Gordan coefficient [18]:

$$\langle \mathbf{R}\, Y\, I\, I_3 | \mathbf{r}\, y\, i\, i_3\, \mathbf{r}'\, y'\, i'\, i'_3 \rangle = F(\mathbf{R}, Y, I; \mathbf{r}, y, i, \mathbf{r}', y', i') \times \langle I\, I_3 | i\, i_3\, i'\, i'_3 \rangle \ . \tag{16}$$

$F(\mathbf{R}, Y, I; \mathbf{r}, y, i, \mathbf{r}', y', i')$ is the iso-scalar function which cab be found in the tables of Ref. [18]. For example, from Table 10 in Ref. [18] we get

$$F(D^{-\prime}_{s,15} \to D_s \eta) = \frac{\sqrt{3}}{2} \ , \tag{17}$$

$$F(D^{-\prime}_{s,15} \to K^- \bar{D}^0) = -\frac{1}{2} \ . \tag{18}$$

The SU(2) Clebsch-Gordan coefficient is 1 for $D^{-\prime}_{s,15} \to D_s \eta$ and $\frac{1}{\sqrt{2}}$ for $D^{-\prime}_{s,15} \to K^- \bar{D}^0$. Putting everything together we obtain the relative ratio of the decay C. G. coefficients again

$$\left| \frac{\lambda(D^{-\prime}_{s,15} \to K^- \bar{D}^0)}{\lambda(D^{-\prime}_{s,15} \to D_s \eta)} \right| = \frac{1}{\sqrt{6}} \ . \tag{19}$$

$D_{s,\bar{6}}^{--}$		$D_{s,\bar{6}}^{-}$		$D_{s,\bar{6}}^{0}$	
K^-D^-	-1	$K^-\bar{D}^0$	$-\frac{1}{\sqrt{2}}$	$\pi^+D_s^-$	-1
$\pi^-D_s^-$	1	$\bar{K}^0D^-$	$\frac{1}{\sqrt{2}}$	$\bar{K}^0\bar{D}^0$	1
		$\pi^0D_s^-$	1		
$D_{\bar{6}}^{-}$		$D_{\bar{6}}^{0}$		$D_{\bar{s},\bar{6}}^{0}$	
$\pi^-\bar{D}^0$	$-\frac{1}{\sqrt{2}}$	$\pi^0\bar{D}^0$	$-\frac{1}{2}$	$K^0\bar{D}^0$	-1
π^0D^-	$\frac{1}{2}$	$\eta_8\bar{D}^0$	$\frac{\sqrt{3}}{2}$	K^+D^-	1
η_8D^-	$\frac{\sqrt{3}}{2}$	π^+D^-	$-\frac{1}{\sqrt{2}}$		
$K^0D_s^-$	$\frac{1}{\sqrt{2}}$	$K^+D_s^-$	$\frac{1}{\sqrt{2}}$		

TABLE IV: Couplings of the heavy tetraquark anti-sextet T_{ij} with the heavy meson triplet T^i and pseudoscalar meson octet M^i_j. The universal coupling constant is omitted.

D_{15}^{+}		D_{15}^{0}		D_{15}^{-}		D_{15}^{--}		$D_{15}^{0\prime}$	
$\pi^+\bar{D}^0$	-1	$\pi^0\bar{D}^0$	$\frac{2}{\sqrt{6}}$	π^0D^-	$\frac{2}{\sqrt{6}}$	π^-D^-	1	$K^+D_s^-$	$\frac{3}{2\sqrt{6}}$
		π^+D^-	$-\frac{1}{\sqrt{3}}$	$\pi^-\bar{D}^0$	$\frac{1}{\sqrt{3}}$			π^+D^-	$-\frac{1}{2\sqrt{6}}$
								$\pi^0\bar{D}^0$	$-\frac{1}{4\sqrt{3}}$
								$\eta_8\bar{D}^0$	$-\frac{3}{4}$
$D_{15}^{-\prime}$		$D_{s,15}^{0}$		$D_{s,15}^{-}$		$D_{s,15}^{--}$		$D_{s,15}^{-\prime}$	
$K^0D_s^-$	$\frac{3}{2\sqrt{6}}$	$\pi^+D_s^-$	$-\frac{1}{\sqrt{2}}$	$\pi^0D_s^-$	$\frac{1}{\sqrt{2}}$	$\pi^-D_s^-$	$\frac{1}{\sqrt{2}}$	$\eta_8D_s^-$	$-\frac{\sqrt{3}}{2}$
η_8D^-	$-\frac{3}{4}$	$\bar{K}^0\bar{D}^0$	$-\frac{1}{\sqrt{2}}$	$K^-\bar{D}^0$	$\frac{1}{2}$	K^-D^-	$\frac{1}{\sqrt{2}}$	$K^-\bar{D}^0$	$-\frac{1}{2\sqrt{2}}$
π^0D^-	$\frac{1}{4\sqrt{3}}$			$\bar{K}^0D^-$	$-\frac{1}{2}$			$\bar{K}^0D^-$	$-\frac{1}{2\sqrt{2}}$
$\pi^-\bar{D}^0$	$-\frac{1}{2\sqrt{6}}$								
$D_{\bar{s},15}^{+}$		$D_{\bar{s},15}^{0}$		$D_{\bar{s},15}^{-}$		D_{ss}^{-}		D_{ss}^{--}	
$K^+\bar{D}^0$	1	K^+D^-	$\frac{1}{\sqrt{2}}$	K^0D^-	1	$\bar{K}^0D_s^-$	-1	$K^-D_s^-$	1
		$K^0\bar{D}^0$	$\frac{1}{\sqrt{2}}$						

TABLE V: Couplings of the heavy tetraquark 15-plet T^{ij}_k with usual meson octet M^i_j and the heavy meson triplet T^i. The universal coupling constant is omitted.

In fact, an even more transparent derivation of the relative ratio of the decay coupling constants is possible if we assume the "fall-apart" decay mechanism for tetraquarks. With the flavor wave function of $D_{s,15}^{-\prime}$ in Table III, only the first two terms contribute to $K^-\bar{D}^0$ decay mode while every piece contributes to $D_s\eta$ mode. The ratio of their coupling constants is simply

$$|\lambda(D_{s,15}^{-\prime} \to K^-\bar{D}^0) : \lambda(D_{s,15}^{-\prime} \to D_s\eta)| = (1+1) : \frac{1}{\sqrt{6}}(1+1+1+1+(-2)*(-2)*2) = 1 : \sqrt{6}\,. \tag{20}$$

The last factor two arises because there are two possible ways to get an $s\bar{s}$ from $ss\bar{s}$. Once again we reproduce this ratio.

Based on the above argument, we propose that $D_{sJ}^{+}(2632)$ is very probably a tetraquark state in the $SU(3)_F$ 15 representation with the quantum number $I = 0, J^P = 0^+$.

III. DISCUSSIONS

We may also perform a rough estimate of the mass of $D_{s,15}^{-\prime}$ with the flavor wave function. If we use constituent quark masses: $m_u = m_d = 310$ MeV, $m_s = 450 MeV$ and $m_c = 1430$ MeV, we have

$$M_{D_{s,15}^{-\prime}} = \frac{1}{8}[4(m_u+m_u+m_s)+4(m_s+m_s+m_s)] + m_c = m_u + 2m_s + m_c = 2640\text{MeV}. \tag{21}$$

Using the well-known Gell-Mann-Okubo formula, it's easy to derive the mass relations between the tetraquark states within the same multiplet

$$M = a + b[I(I+1) - \frac{1}{4}Y^2] + cY. \tag{22}$$

For the heavy tetraquark anti-sextet,

$$M_{D_{\bar{s},\bar{6}}} - M_{D_{\bar{6}}} = M_{D_{\bar{6}}} - M_{D_{ss}}. \tag{23}$$

For the heavy tetraquark 15-plet, we find

$$M_{D_{\bar{s},15}} - M_{D'_{15}} = M_{D'_{15}} - M_{D'_{s,15}} \tag{24a}$$

$$M_{D_{15}} - M_{D_{s,15}} = M_{D_{s,15}} - M_{D_{ss}} \tag{24b}$$

$$M_{D_{\bar{s},15}} + 3M_{D_{s,15}} = 2(M_{D_{15}} + M_{D'_{s,15}}). \tag{24c}$$

It is very interesting to note that there are three manifestly exotic four quark states: $D^0_{\bar{s},\bar{6}}, D^0_{s,\bar{6}}, D^{--}_{s,\bar{6}}$. There are nine manifestly exotic four-quark states: $D^+_{\bar{s},15}, D^0_{\bar{s},15}, D^-_{\bar{s},15}, D^+_{15}, D^{--}_{15}, D^0_{s,15}, D^{--}_{s,15}, D^-_{ss}, D^{--}_{ss}$. If $D_{sJ}(2632)$ is really a member of the tetraquark states in the 15 representation, these exotic states should appear as partners of $D_{sJ}(2632)$. We strongly call for experimental search of these interesting states. Some of them have a unique decay channel such as $D^+_{15} \to \bar{D}^0\pi^+$, $D^{--}_{15} \to D^-\pi^-$ etc.

Replacing the charm quark in $D^+_{sJ}(2632)$ by the bottom quark, we get bottom tetraquark state $B^0_{sJ}(5832)$ where we have assumed the mass difference between $D^+_{sJ}(2632)$ and $B^0_{sJ}(5832)$ is simply $m_b - m_c = 3200$ MeV. $B^0_{sJ}(5832)$ is also expected to be a narrow resonance above threshold with a dominant decay mode $B_s\eta$.

In Ref. [13] Maiani et al. suggested that $D^+_{sJ}(2632)$ is a $cd\bar{d}\bar{s}$ state to a good extent while its anomalous decay ratio is caused by isospin breaking. In Ref. [15] it was also suggested that $D^+_{sJ}(2632)$ is a cryptoexotic tetraquark baryonium state $cd\bar{d}\bar{s}$ [15]. Ref. [14] tried to identify all three narrow charm-strange mesons $D_{sJ}(2137)$, $D_{sJ}(2457)$, $D^+_{sJ}(2632)$ as four-quark states. Ref. [16] suggested that $D^+_{sJ}(2632)$ could be the first radial excitation of $D^*_s(2112)$ state and the unusual decay pattern might be explained by the node structure of the wave functions. Ref. [16] also dealt with the possibility of interpreting $D^+_{sJ}(2632)$ as a diquark and anti-diquark bound state. Ref. [17] suggested the same scheme for the narrow width of $D^+_{sJ}(2632)$. However it was pointed out that the relative branching ratio of such a assignment still disagrees with SELEX experiment [17].

We have inferred from the unusual decay pattern that the narrow resonance observed by SELEX Collaboration is very probably a four quark state with the quark content $\frac{1}{2\sqrt{2}}(ds\bar{d} + sd\bar{d} + su\bar{u} + us\bar{u} - 2ss\bar{s})\bar{c}$. We have made a systematic analysis of the charm tetraquark states and have explicitly demonstrated how this unusual decay pattern occurs.

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